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**A METHOD OF CALCULATING THE EFFECTIVE INTENSITY
OF MULTIPLE-FLICK FLASHTUBE SIGNALS**

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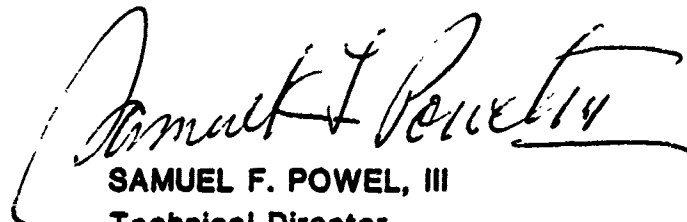
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Technical Director

U.S. Coast Guard Research and Development Center
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16. Abstract <p>The purpose of this work was to devise a method of determining the effective intensity of light flashes composed of multiple pulses (flicks) of light. Detection thresholds were measured for such flashes when the flick frequency and flash duration were varied. Thresholds decreased with increasing flick frequency and flash duration. At each flick frequency the relationship between threshold and flash duration was well-characterized by the Blondel-Rey relation ($a=0.2$) provided a multiplicative frequency-dependent fitting parameter was chosen. The fitting parameter, β, increased linearly with frequency between 5 and 20 Hz. A method of determining effective intensity was described which uses the flick frequency, number of flicks and the calculated effective intensity of a single flick to arrive at the solution. It was concluded that this method should be used for all multiple flick signals provided the single-flick duration is less than 0.01 sec and the frequency is between 5 and 20 Hz. The method of Allard should not be used, as it consistently overestimates effective intensity.</p> <p><i>References included</i></p>					
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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
in	inches	* 2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
AREA				
in ²	square inches	6.5	square centimeters	cm ²
ft ²	square feet	0.09	square meters	m ²
yd ²	square yards	0.8	square meters	m ²
mi ²	square miles	2.6	square kilometers	km ²
	acres	0.4	hectares	ha
MASS (WEIGHT)				
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
VOLUME				
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft ³	cubic feet	0.03	cubic meters	m ³
yd ³	cubic yards	0.76	cubic meters	m ³
TEMPERATURE (EXACT)				
°F.	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

* 1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures. Price \$2.25. SD Catalog No. C13.10.286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
AREA				
cm ²	square centimeters	0.16	square inches	in ²
m ²	square meters	1.2	square yards	yd ²
km ²	square kilometers	0.4	square miles	mi ²
ha	hectares (10,000 m ²)	2.5	acres	
MASS (WEIGHT)				
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
VOLUME				
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	0.125	cups	c
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m ³	cubic meters	35	cubic feet	ft ³
m ³	cubic meters	1.3	cubic yards	yd ³
TEMPERATURE (EXACT)				
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

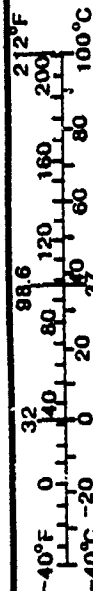


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INTRODUCTION

A flashtube is a capacitive discharge device capable of emitting brilliant flashes of light in extremely brief time periods (on the order of microseconds). The highly intense flashtube burst can be detected at great distances and has been noted as a conspicuous signal in a typical aid-to-navigation system (Devoe and Abernethy, 1975). Moreover, the efficiency of converting input energy to visible output is greater than that of an incandescent light (Montonye and Clark, 1970). These factors make the flashtube attractive as an aid to navigation.

There are three major disadvantages associated with the use of flashtubes. The intense nature of the flick tends to momentarily blind the close observer (Murphy, 1981). Also, the duration of the single flick is so brief that mariners have difficulty fixing the exact location in the visual field (Murphy, 1981). Finally, mariners report difficulty judging the distance to the flashing source (Murphy, 1981). The latter two difficulties can be ameliorated by presenting several flicks in rapid succession such that the appearance is not one of individual flicks, but a longer duration flash. Previous studies have shown that individuals can take line-of-sight bearings with greater speed and accuracy when the flash duration is increased in this way (Thacker, 1984).

The detection distance of a lighted aid to navigation is valuable information since it not only allows one to calculate the range at which a light will become visible, but it is also one measure of the signal effectiveness of the aid. A typical aid-to-navigation system is composed of both steady and flashing lights. The detection distance of a steady light, where intensity does not vary with time, can be calculated from the familiar Allard's Law (Allard, 1876):

$$E = I \cdot D / D^2$$

where E is the illuminance threshold of the eye (typically 0.67 sea-mile candles; U.S. Coast Guard, 1970), I is the intensity of the light, D is

the transmissivity of the atmosphere, and D is the distance at which the light is visible. As the intensity of a flashing light source is a function of time, the detection distance can be calculated using Allard's Law provided that a steady-light-equivalent intensity, termed the effective intensity of the light, can be determined. Effective intensity is defined as follows:

If a flash is found to be just seen in conditions in which a steady light of intensity I_e is also just seen at the same distance and in the same atmospheric conditions, the flash is said to have an effective intensity I_e . (IALA, 1978, p.21)

The three generally accepted methods of calculating the effective intensity of a single flash are the methods of Allard (Allard, 1876; not to be confused with Allard's Law discussed above), Schmidt-Clausen (Schmidt-Clausen, 1970; 1971), and Blondel-Rey-Douglas (Blondel and Rey, 1911; Douglas, 1957). All these methods are condensed and described by The International Association of Lighthouse Authorities, (IALA) (1978).

As noted above, the increased flash duration of the multiple-flick flash is desirable, but to incorporate these multiple-flick flashtube devices in an aid-to-navigation system requires a method of specifying its detection range. The International Association of Lighthouse Authorities (IALA) formally recognized that of the three single-flash methods of calculating effective intensity, only the method of Allard is appropriate for calculating the effective intensity of multiple-flick flashes.

The reason for recommending ... the method of Allard for trains of rapidly repeated flashes was that this method would yield an effective intensity that increased with increasing number of flashes in the train and approached asymptotically a steady-state response that for very rapid rates was identical with Talbot's Law. The other two methods could not yield any satisfactory effective intensity for trains of flashes. It cannot, however, be said that there is any direct experimental confirmation of the effective intensity obtained by the Allard method for repeated flashes. (IALA, 1981, p. 27)

The method of Allard involves lengthy computer calculations of the explicit solution of a differential equation (IALA, 1978). The primary purpose of this work was to find a simple, accurate method of determining the effective intensity of multiple flick signals based on the characteristics of the signal. A secondary goal of this work was to provide the missing experimental confirmation of the Allard method.

DEFINITIONS

A single light pulse from a flashtube is called a flick. When several flicks are presented in rapid succession such that dark periods are not distinguished between the individual flicks, it is referred to as a multiple-flick flash. The rate at which the flicks are delivered in a multiple-flick flash is termed the flick frequency. The flash duration or flash length is the time between onset of the first flick and the cessation of the last flick and is a function of the flick frequency and the number of flicks. Figure 1 provides two examples of multiple-flick signals. The bottom portion of Figure 1 shows relative intensity as a function of time for a 20 Hz, 13-flick signal. The time between each flick is $1/\text{flick frequency}$, which in this case is 0.05 seconds. The flash duration is 0.6 seconds. In the upper portion of the figure, a 5 Hz, 4-flick signal is shown. Each flick is delivered every 0.2 second. As with the 20 Hz signal, the flash duration is 0.6 sec, though the number of flicks and total integrated light intensities of the two signals are different.

APPARATUS

Figure 2 shows a schematic of the apparatus used for data collection. A flashtube (Automatic Power Inc., Part 9001-0295) was installed inside an integrating sphere. A 0.025 inch aperture was attached to the output of the integrating sphere and defined the source size. A variable neutral density wedge provided computer control of illuminance of the signal. The signal was reflected off a mirror and superimposed on a low luminance (0.0045 ft-Lambert) background provided by a Kodak slide projector.

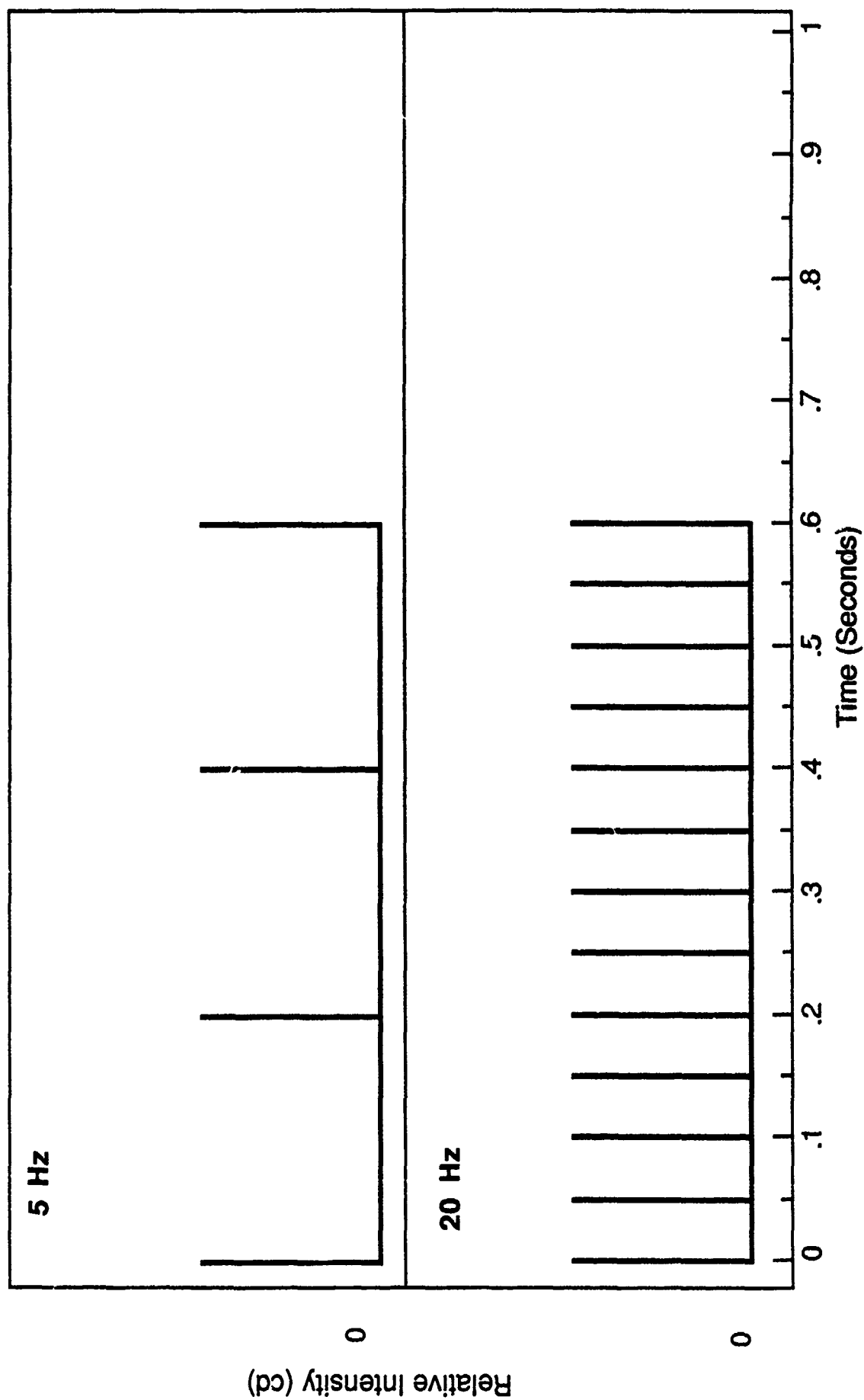


Figure 1. Example of two multiple flick signals with equal flash duration and unequal flick frequency

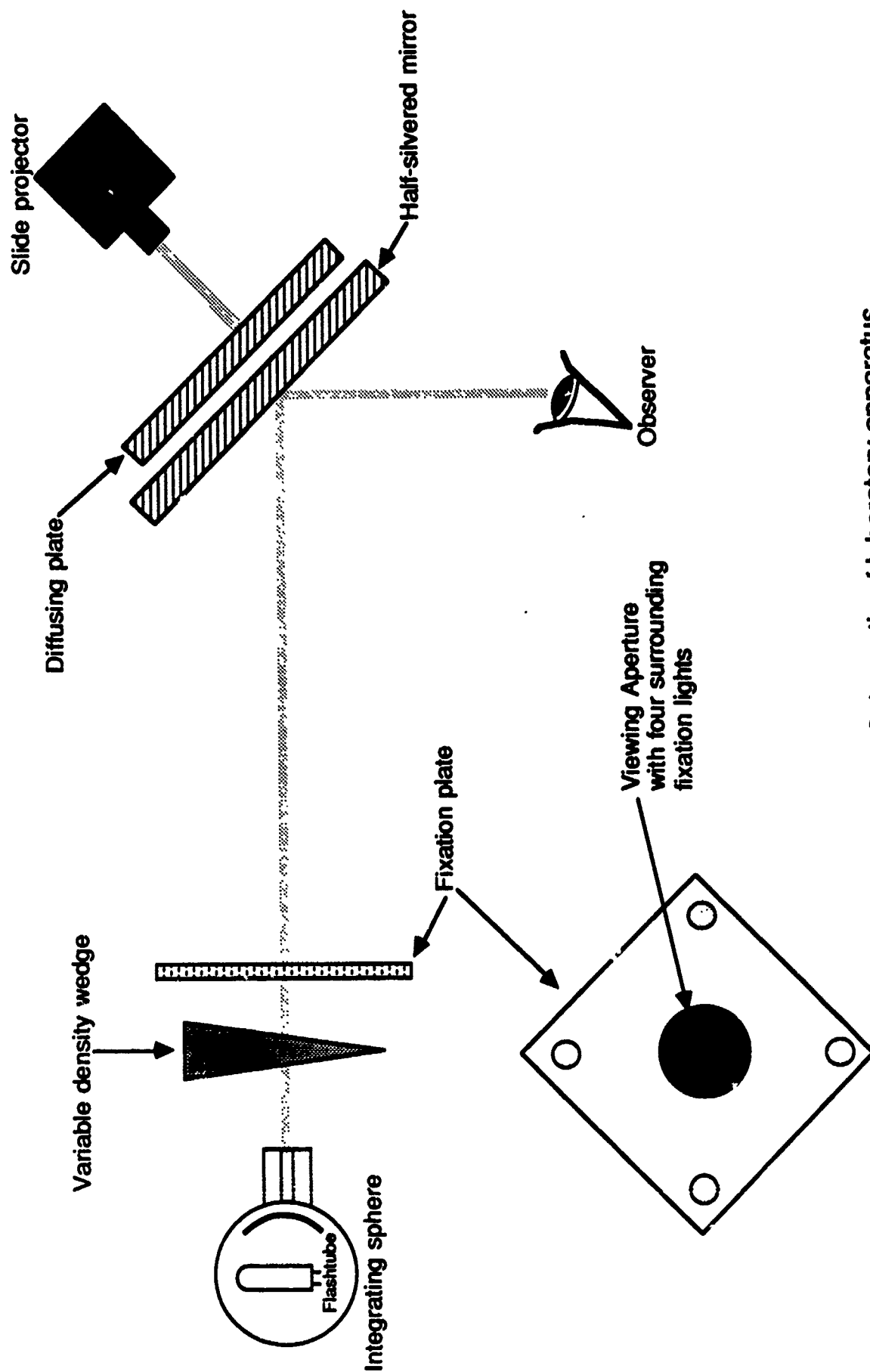


Figure 2. Schematic of laboratory apparatus

The signal appeared as a point source (actual angular diameter of 0.0003 mrad) when viewed from 83.25 inches. The background subtended approximately 1.0 rad by 1.0 rad. To minimize the observer's uncertainty of the position of the signal, four small, low-intensity fixation points were provided, each 17.5 mrad from the signal location.

The flashtube circuitry was modified so that it could be triggered by a computer pulse. A single output flick was presented for each input trigger with the maximum rate being 50 flicks per second.

CALIBRATION

Figure 3 shows a plot of the intensity as a function of time for a single near-threshold flick. To obtain this curve, an EG&G photomultiplier tube (PMT) with photometric filter was positioned in the apparatus where the observer's eye was typically positioned. The PMT, which had a rise time of less than 10 nanoseconds, was calibrated against an EG&G Model 555 Photometer System, using a steady light, so that the relationship between illuminance and output voltage from the PMT was known.

This figure shows that the peak output occurs at about 20 μ sec after flick onset and the intensity decays to 10 percent of peak after 55 μ sec, with negligible low level output for as long as about 85 μ sec after onset.

PROCEDURE

Detection thresholds were obtained for a total of 34 separate signals. Table I shows the six flick frequencies that were used, the number of flicks provided at each frequency, and the corresponding flash duration (see Equation (4)).

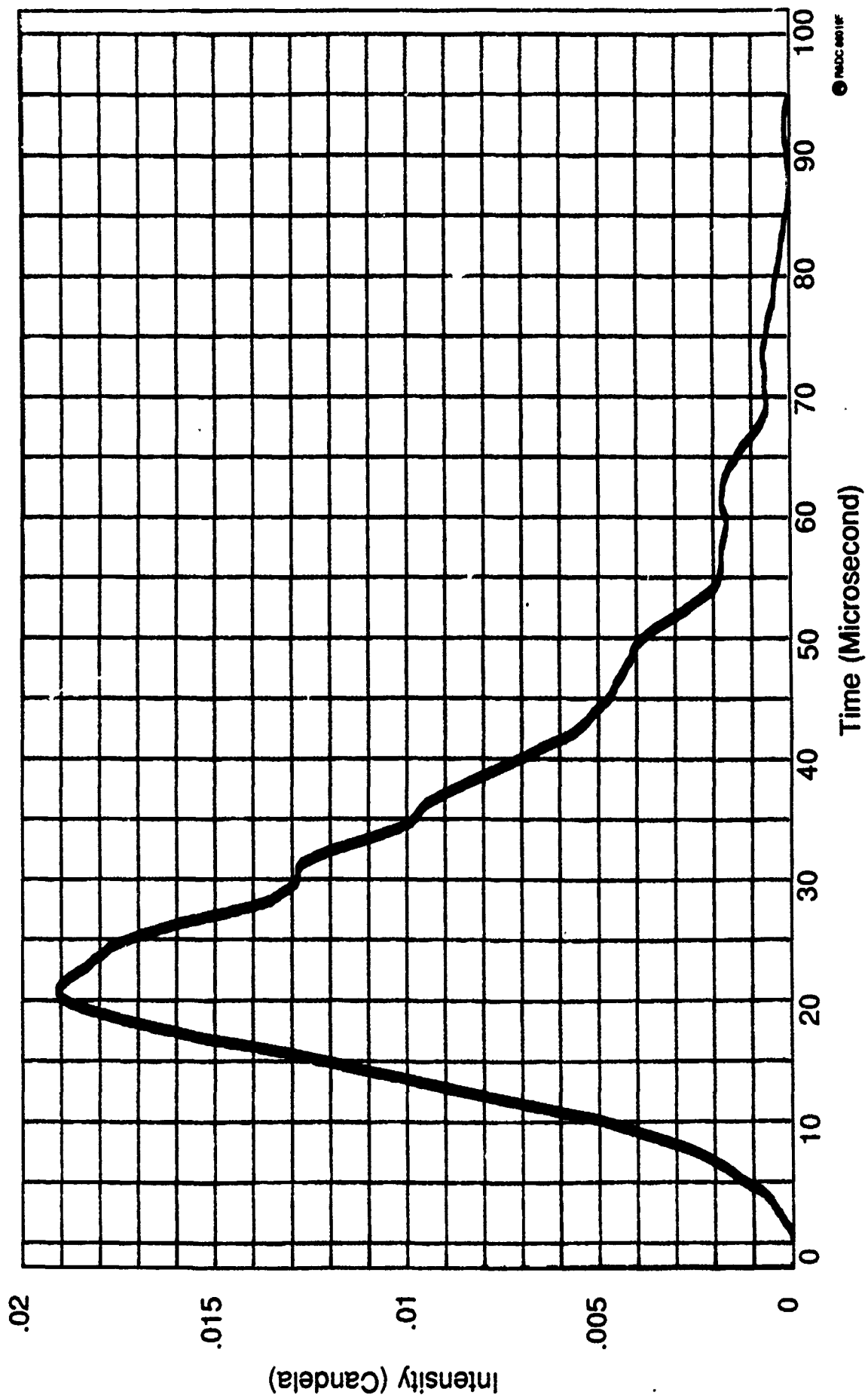


Figure 3. Intensity profile of a single flick

TABLE I
TEST SIGNALS

Flick Frequency (Hz)	Numbers of Flicks	Flash Durations (Seconds)
5	1,2,3,4	.000, .200, .400, .600
8	1,2,4,6	.000, .125, .375, .625
11	1,3,5,7,9	.000, .182, .363, .546, .727
14	1,3,5,7,9,11	.000, .143, .286, .429, .572, .714
17	1,3,5,7,9,11,13	.000, .118, .235, .353, .471, .588, .706
20	1,3,5,7,9,11,13,15	.000, .100, .200, .300, .400, .500, .600, .700

A staircase procedure was used to measure thresholds simultaneously for all the signals of a particular frequency. On a given trial, one of the 34 signals was presented and the observers responded as to whether or not the signal was detected by pressing one of two computer-readable switches. If the signal was not detected, the illuminance was raised by 0.1 log units (25.9%). When the signal was detected three consecutive times, the illuminance was decreased by 0.1 log units. This illuminance "staircase" continued until the illuminance had reversed direction eight times. Threshold was taken to be the mean of the peak illuminances where the staircase reversed direction. This procedure yields a threshold that corresponds to approximately a 79% probability of detection (Wetherill and Levitt, 1965).

Four observers participated in this experiment. Observers dark adapted for at least 20 minutes before data collection began. All viewing was done monocularly (one eye) primarily due to apparatus limitations.

The test signals were always provided in the center of the four light fixation target (see Figure 2) and observers were required to fixate at this point throughout the experiment.

RESULTS

Figure 4 shows one observer's thresholds as a function of flash duration for six flick frequencies. Flash duration is defined to be the time from the start of the first flick to the end of the last flick. Threshold is defined as the illuminance of the signal that could be detected 79% of the time. Since the illuminance of each flick varies with time, the peak illuminance is used as the measure of threshold.

For all frequencies, as flash duration increased, lower peak illuminance was required to detect the light, and thus the threshold is considered to have decreased. Moreover, as frequency increased, and thus the number of flicks per flash increased, thresholds also decreased.

As in any study of visual sensitivity, observers have different thresholds (Hecht, et. al., 1942). In this experiment, the thresholds of the most sensitive and least sensitive observers differed by more than a factor of two. Since concern here is not with an absolute measure of threshold, but rather a relative measure of how threshold changed with flash duration and frequency, all observer one-flick thresholds (flash duration = 80 μ sec) were normalized to 1.0. This means that thresholds at all other flash durations were proportionately less than 1.0, revealing the extent to which the illuminance of these other signals could be reduced, relative to the one-flick threshold, to bring it to the threshold criterion. Moreover, since our interest was with effective intensity and not threshold, the data were converted from a threshold ordinate to an effective intensity ordinate. As two signals at threshold have identical effective intensities, the data of Figure 4 represent the peak illuminances of various test signals of equal effective intensities. The threshold ordinate of Figure 4 can be converted to an effective intensity ordinate by taking the reciprocal of threshold. That is, if one signal has a threshold that is 0.5 times that of another signal, then it has twice the effective intensity.

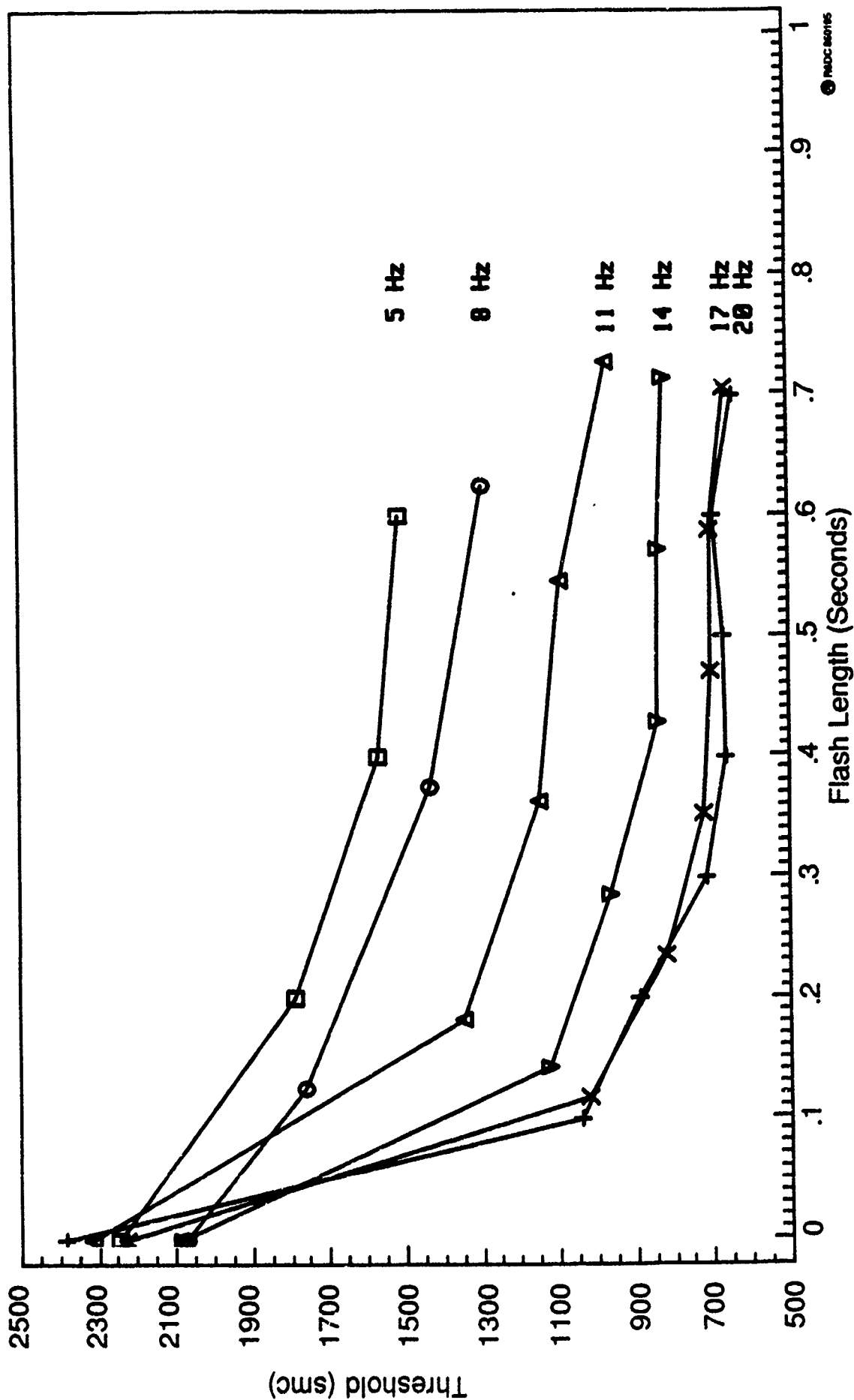


Figure 4. Observer thresholds as a function of flash duration at six frequencies

Figure 5 shows the relative effective intensity functions of the six test frequencies. The squares represent the mean of the four observers, and the vertical bars are ± 1.0 standard error of the mean. The solid curve through the data is a theoretical function fit to the data and is discussed in detail below. The circles show the predictions of the Allard integral, the preferred method of calculating effective intensity of multiple-flick signals (IALA, 1978)

It is clear that the Allard method overestimates the effective intensity of the multiple-flick signals. The amount by which effective intensity is overestimated increases with frequency and flash duration. For example, at 20 Hz the Allard method overestimates effective intensity by as much as 22 percent.

The solid curves through the data are best fits of the function

$$I_e = 1.0 + \beta * [t / (a + t)] \quad (1)$$

where β is a fitting parameter, t is flash duration and a is the constant of 0.2. This is essentially the Blondel-Rey relation (Blondel and Rey, 1911). The constant 1.0 was added in keeping with the normalization performed on the data. By optimizing β , it was possible to fit the group data at each frequency with this function, as shown by the solid curves of Figure 5.

The β providing the best fit at each frequency is shown in Figure 6. The observer data are shown as squares and the Allard calculation as circles. The lines are least-square fits to the data.

As frequency increases, the fitted β increases. Again, as noted above, the fits for the Allard predictions are greater than those for the observer data. The β fits for the Allard predictions fall along a straight line with slope of 0.243 and intercept of -0.488. The observer data can be reasonably approximated by a straight line with slope of 0.203 and intercept of -0.577.

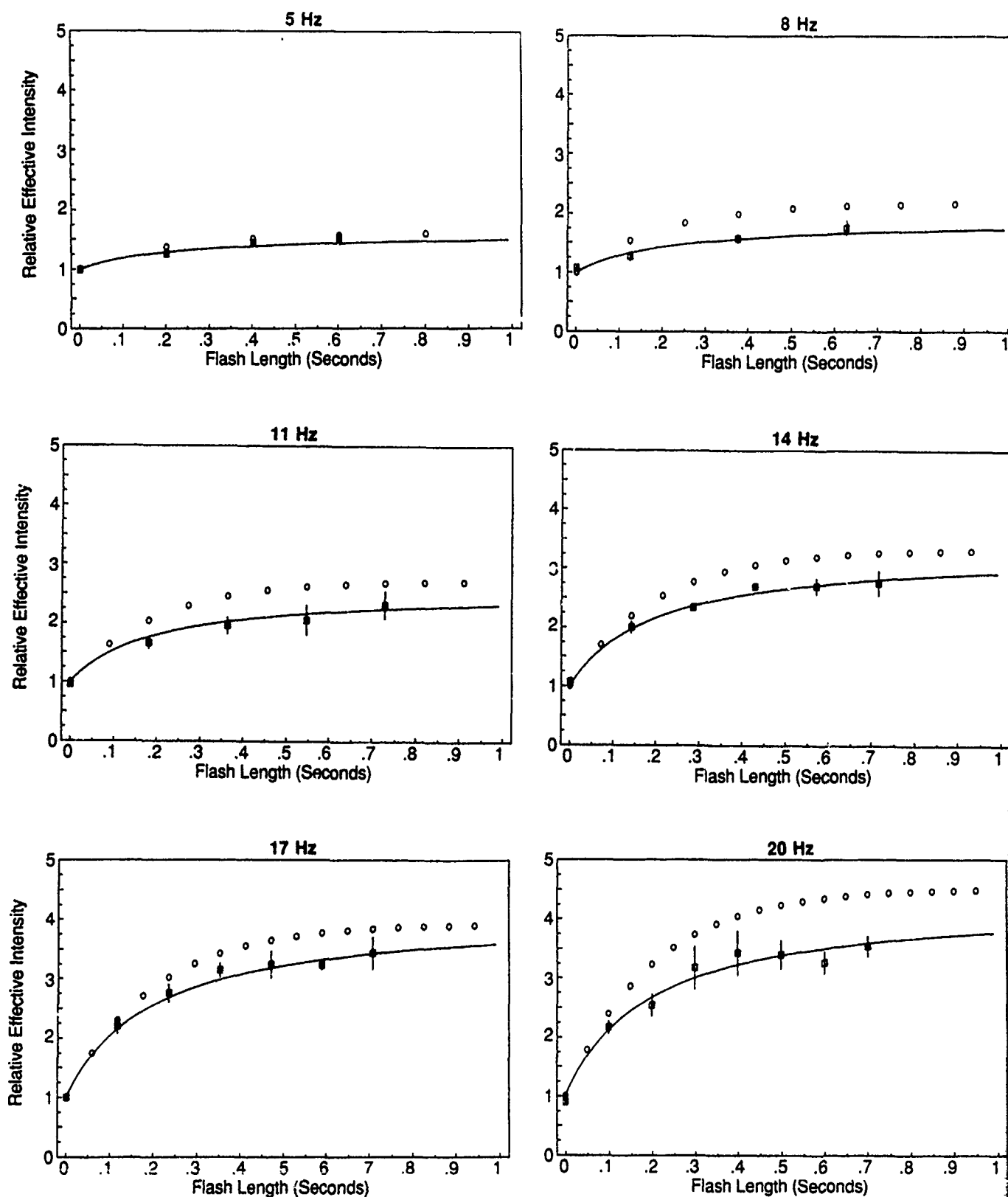


Figure 5. Relative effective intensity functions

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DISCUSSION

The purpose of this experiment was to establish a method of specifying the effective intensity of multiple-flick flashes. It has been shown that for each flick frequency, observer data can be fit with a Blondel-Rey equivalent function (Figure 5) having a frequency-dependent fitting parameter, β (Figure 6). Had the thresholds been independent of frequency, the ratio of the effective intensities at a particular flash duration would have been the same as the ratio of the total energy in the flashes regardless of frequency. This is not the case as can be seen in Figure 5. A 13-flick 20 Hz signal and a 4-flick 5 Hz signal both have flash durations of 0.600 seconds. The ratio of the total energies of these two signals is 3.25, yet the ratio of the effective intensities is 2.30. Consequently, a frequency dependent relationship is required, as shown in Figure 6.

Proposed Method of Calculating Effective Intensity

For any multiple-flick signal the effective intensity can be determined by using Figure 5 as a nomogram and finding, along the ordinate, the value of the relative effective intensity for the appropriate frequency and flash duration. This value, when multiplied by the calculated effective intensity of a single flick, yields the effective intensity of the signal.

An alternative, but equivalent, approach is to derive the equations that can be used to calculate the effective intensity. Equation (1), which was used to fit the observer data of Figure 5, provides the relative effective intensity of any signal provided the fitting parameter, β , is known. The effective intensity, I_e , of a multiple-flick flash can be determined from

$$I_e = I_{e1} * 1.0 + \beta [t / (a + t)] \quad (2)$$

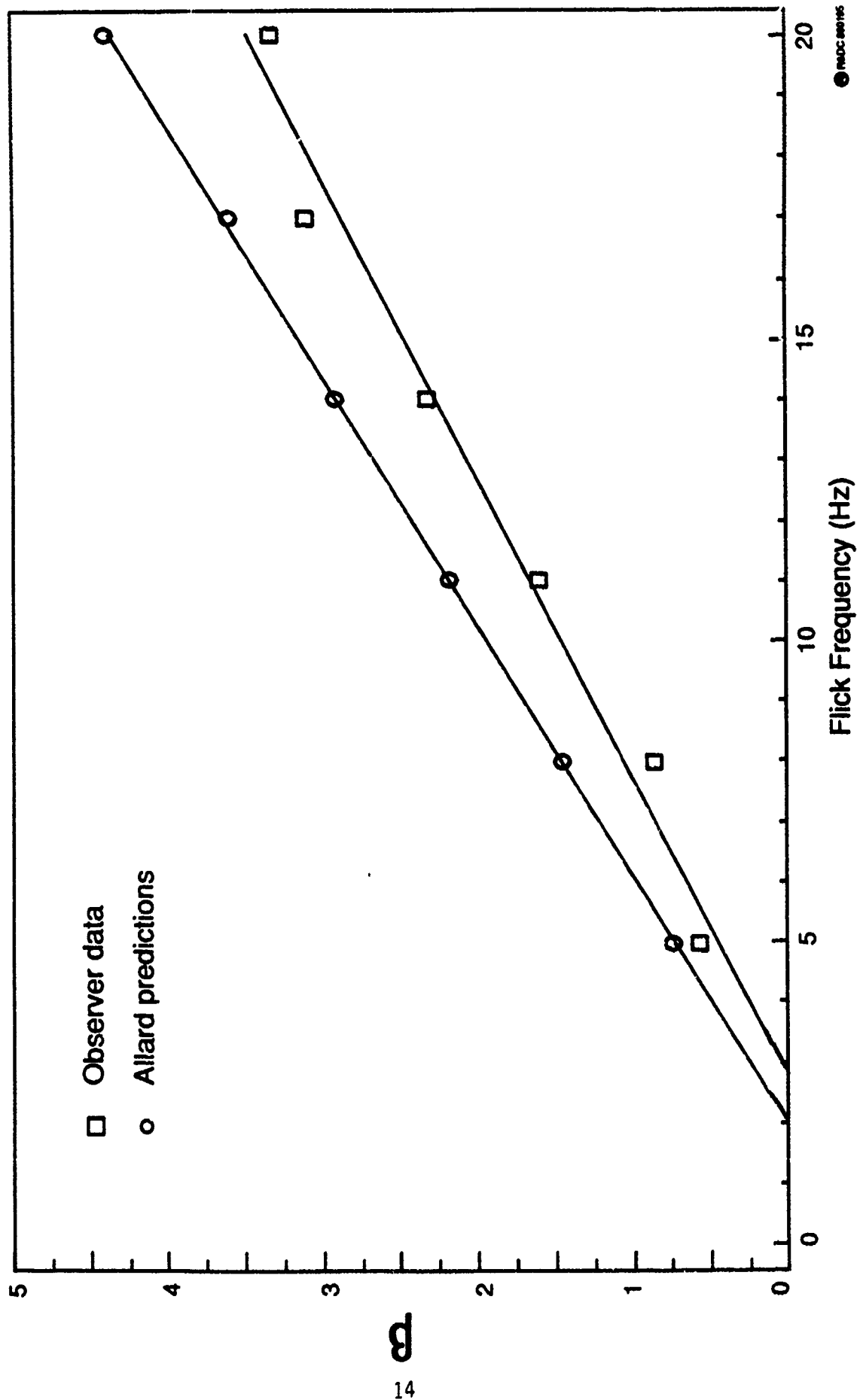


Figure 6. Best fitting β of theoretical function for observer data and Allard predictions ($a = 0.2$)

I_{ef} is the effective intensity of a single flick. To calculate this single flick effective intensity, any of the three methods proposed by IALA are sufficient (IALA, 1978). In our calculations the three methods yielded nearly identical results for the flick shown in Figure 3. The calculated effective intensities from these three methods are shown in Table II.

TABLE II
Single Flick Effective Intensities

<u>Method</u>	<u>Effective Intensity (candelas)</u>
Schmidt-Clausen	4.6189×10^{-7}
Blondel-Rey-Douglas	4.6170×10^{-7}
Allard	4.6800×10^{-7}

The value β can be found from the least-square fit in Figure 6 given the flick frequency. It can be calculated by:

$$\beta = (0.203 * f) - 0.577 \quad (3)$$

where f is frequency in Hz.

Flash duration, t , is calculated by

$$t = (1 / f) * (n - 1) + d, \quad (4)$$

where f is frequency in Hz, n is the number of flicks in the flash, and d is the duration of a single flick. This equation simply calculates the time between the start of the first flick and the end of the last flick.

Table III provides the solution of the above equations for flick frequencies between 5 and 20 Hz and various numbers of flicks. The effective intensity can be determined by multiplying the appropriate tabulated value in Table III by the effective intensity of a single flick.

Flick Duration

The method proposed here is based on threshold measurements for signals with the 80 μ sec flick profile of Figure 3. Not all flicks or light pulses have the same temporal profile, and thus the generality of this method for other flick profiles must be addressed. It is well established that the shape of a light pulse does not affect threshold or effective intensity if its duration is less than the critical duration (i.e. Bloch's Law is obeyed) (Bloch, 1885; Blondel and Rey, 1911). Within certain time intervals, the eye acts as a perfect integrator, and thus pulse shape is irrelevant. While the time period over which Bloch's Law is obeyed varies with many stimulus conditions (Bartlett, 1965) it can conservatively be estimated at 0.01 sec. It appears that as long as the flick duration is less than 0.01 seconds this method can be used. While this has not been verified empirically in this work, two considerations support this conclusion. First, the effective intensity, as calculated by any of the three methods of IALA (1978), is independent of pulse shape for pulses between 0.0 and 0.01 sec. Second, the amount by which Allard's method overestimates effective intensity is constant provided the flick duration is less than 0.01 sec. It is concluded that this method of calculating effective intensity can be used for any multiple pulse light flash as long as each pulse is less than 0.01 sec.

The Visual Time Constant a

It has been internationally agreed (IALA, 1978) that for nighttime observation the visual time constant a , used for calculations of effective intensity, should be equal to 0.2. Nighttime observation is assumed to be at a background luminance less than 0.1 cd/m^2 (IALA, 1978). The background used

TABLE III
Relative Effective Intensities of Common Flashtube Signals
Numbers of Flicks Per Flash

Flick Freq. (Hz.)	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
5	1.219	1.292	1.329	1.350															
6	1.291	1.401	1.458	1.493	1.517														
7	1.352	1.497	1.575	1.625	1.659	1.684													
8	1.403	1.582	1.683	1.748	1.793	1.827	1.852												
9	1.447	1.658	1.781	1.862	1.919	1.961	1.994	2.020											
10	1.485	1.727	1.872	1.969	2.038	2.090	2.130	2.162	2.189										
11	1.518	1.789	1.956	2.068	2.150	2.212	2.260	2.299	2.331	2.357									
12	1.547	1.845	2.033	2.162	2.256	2.327	2.384	2.430	2.468	2.499	2.526								
13	1.573	1.897	2.105	2.250	2.357	2.437	2.504	2.556	2.600	2.637	2.668	2.695							
14	1.597	1.944	2.172	2.333	2.452	2.544	2.618	2.679	2.728	2.770	2.805	2.837	2.864						
15	1.612	1.989	2.234	2.411	2.543	2.645	2.728	2.795	2.851	2.899	2.939	2.974	3.005	3.033					
16	1.637	2.028	2.293	2.484	2.629	2.742	2.833	2.908	2.971	3.024	3.069	3.109	3.143	3.174	3.201				
17	1.654	2.065	2.348	2.554	2.711	2.835	2.935	3.017	3.086	3.145	3.195	3.240	3.278	3.312	3.342	3.370			
18	1.670	2.100	2.399	2.620	2.789	2.923	3.032	3.122	3.198	3.262	3.318	3.367	3.410	3.448	3.482	3.512	3.539		
19	1.684	2.132	2.448	2.682	2.864	3.008	3.126	3.224	3.306	3.377	3.438	3.491	3.538	3.580	3.617	3.651	3.681	3.708	
20	1.698	2.162	2.493	2.742	2.935	3.090	3.217	3.322	3.411	3.488	3.554	3.612	3.654	3.709	3.750	3.786	3.820	3.850	3.877

in this experiment was 0.015 cd/m^2 ; considerably less than the maximum permitted. For the curve fitting performed on the data of Figure 5, \underline{a} was assumed to be 0.2. It can be seen that the theoretical curve does an adequate job of fitting the observer data. It was disturbing, though, that the Allard method overpredicted I_e . As an exercise, the analysis was repeated using different values of \underline{a} in search of an \underline{a} that would bring the observer data and the Allard calculation into agreement. The observer data were refitted with different values of \underline{a} and the Allard calculation was performed with these same values of \underline{a} , and the results compared. Figure 7 shows the best-fitting β for the observer data and the Allard calculation assuming an \underline{a} of 0.155. The least-squares fit to the observer data yields a slope of 0.189 and an intercept of -0.540 while the slope and intercept for the Allard calculations are 0.183 and -0.445, respectively.

Areas of Further Investigation

In this experiment only a single background luminance was used. It is of interest to determine if the slope of the curve in Figure 6 varies with background luminance so the generality of this approach can be assessed. Further, it was argued that the proposed method can be used with many different flick profiles and durations. This argument should be empirically verified.

Another area in which much work is needed is in determining the optimum flick frequency and flash duration. Such an approach must not only take into account the effective intensity of the signal, but must be concerned with speed and accuracy with which a bearing can be taken and must perform a comparative analysis of battery power requirements for such signals. Thacker (1984) showed that as flash duration increases, speed and accuracy in taking a bearing improve. Montonye and Clark (1970) performed a partial analysis of flashtube battery power requirements. Edgerton (1979) has measured the

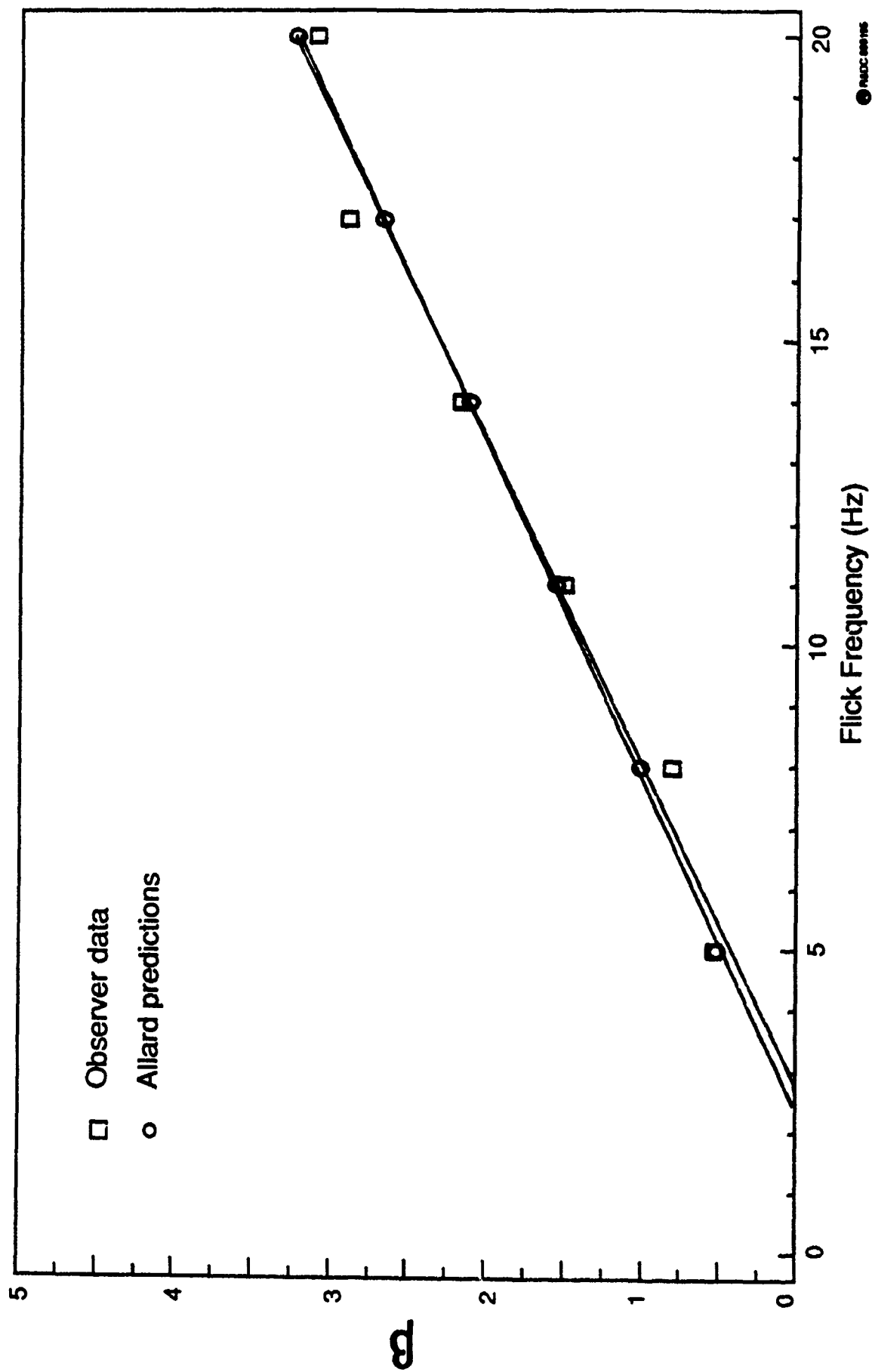


Figure 7. Best fitting β of theoretical function for observer data and Allard predictions ($a = 0.155$)

relationships between the size of the flashtube storage capacitor, initial capacitor charging voltage, the peak output intensity, the electrical input to visual output efficiency, and the flick duration. Before flashtubes are widely deployed in the field, all these approaches to flashtube optimization must be fully analyzed in conjunction with one another.

CONCLUSIONS

Based on the results reported here it is concluded that:

1. The proposed method of calculating effective intensity, I_e , should be used for any multiple-flick signal regardless of the single-flick time-intensity profile, provided the single-flick duration is less than 0.01 sec and the flick frequency is between 5 and 20 Hz. The effective intensity can be calculated from Equations (2), (3) and (4) found in the Discussion section.
2. The method of Allard should not be used for calculating the effective intensity of multiple-flick flashes since it consistently overestimates the effective intensity. The greater the flick frequency, the greater the error.

RECOMMENDATIONS

The purpose of this effort was to determine a means of calculating the effective intensity of a multiple flick signal. The results reported here do not fully address the issue of the optimum flashtube signal to incorporate into field-deployable hardware. There remain several issues that must be resolved before the optimum signal is chosen. Accordingly, it is recommended that:

1. Research be conducted to specify the flashtube energy consumption as a function of number of flicks employed in a flash and the circuitry of the system. This analysis would compare/contrast the results obtained from standard incandescent sources. This work will reveal how signals are limited

by energy consumption. Work should also be done to optimize the flashtube circuitry for Coast Guard applications.

2. Research be sponsored that addresses issues of human performance with respect to flashtube signals. Specifically, problems of depth perception and difficulty in obtaining a fix on the light should be studied more carefully.

3. Once the above results are collected, an optimum range of flashtube signals should be selected based on performance measures, calculated effective intensity and energy consumption considerations.

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